

Formation of the off-center bar in the Large Magellanic Cloud: A collision with a dark satellite ?

Kenji Bekki^{1*}

¹*School of Physics, University of New South Wales, Sydney 2052, NSW, Australia*

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ABSTRACT

Recent observations on structural properties of the Large Magellanic Cloud (LMC) based on the Deep Near-Infrared Southern Sky Survey (DENIS) and Two Micron All-Sky Survey (2MASS) have revealed that the LMC has an off-center bar even in the older stellar populations. Previous dynamical models including tidal interaction between the LMC, the Small Magellanic Cloud (SMC), and the Galaxy, however, did not reproduce so well the older off-center bar. We here show that the off-center bar can be formed if the LMC with an already existing bar can collide with a low-mass Galactic subhalo as massive as $\sim 5 \times 10^8 M_\odot$ (corresponding roughly to a few % of the LMC mass). The simulated stellar distribution after the collision appears to show an “off-center bar”, not because the center of the bar significantly deviates from the dynamical center of the LMC, but because the underlying stellar distribution of the disk is significantly asymmetric with respect to the center of the bar. We discuss whether off-center bars observed in Magellanic-type dwarf galaxies can be formed as a result of tidal interaction with low-mass halos with no or little visible matters.

Key words: Magellanic Clouds – galaxies:structure – galaxies:kinematics and dynamics – galaxies:halos – galaxies:star clusters

1 INTRODUCTION

Recent photometric and spectroscopic observations on structures and kinematics of stars with different ages and metallicities in the LMC have significantly improved our understanding of the dynamical properties (e.g., Cioni et al. 2000; van der Marel 2001, v01; Minniti et al. 2003; Alves 2004; Cole et al. 2005; Grocholski et al. 2006; Olsen & Massey 2007). For example, observational studies based on the DENIS and the 2MASS have revealed that the LMC has the off-center stellar bar in a significantly elongated stellar disk (e.g., v01). Although the spatial distribution of these intermediate-age stellar populations (e.g., AGB/RGB stars) does not show clearly spiral arms (v01), younger stellar populations are observed to show peculiar arms which may have formed from the past tidal interaction between the LMC and the SMC (Olsen & Massey 2007). These observations imply that stellar populations with different ages have different spatial distributions in the LMC.

One of intriguing results as to the dynamical properties of the LMC in these observations is the off-center bar seen in the projected distribution of *intermediate-age stellar*

populations: a prominent off-center bar embedded within its flat disk component was already identified early for the optical image determined largely by the distributions of younger stellar populations (e.g., de Vaucouleurs & Freeman 1972). Recent numerical simulations have shown that the two-dimensional distribution of the B -band surface brightness (μ_B) in the LMC stellar disk after the LMC-SMC-Galaxy interaction about 0.2 Gyr ago appears to have an off-center bar to some extent (Bekki & Chiba 2007; BC07). However, the simulated asymmetric 2D distribution with apparently an off-center bar is due largely to young stars formed in the asymmetric gas (BC07): the spatial distribution of the older stellar populations is highly unlikely to show an off-center bar. Other numerical simulations on dynamical evolution of the LMC also failed to reproduce well the off-center bar (e.g., Bekki & Chiba 2005, BC05; Mastropietro et al. 2005). Thus the origin of the off-center bar is far from being understood well in the context of the past dynamical interaction between the Magellanic Clouds (MCs) and the Galaxy.

The purpose of this Letter is to show, for the first time, that if the LMC can collide with a low-mass subhalo of the Galaxy, the LMC can develop an off-center bar in the old disk. We discuss the masses and orbits of the subhalos required for the formation of the off-center bar based on a large

* E-mail: bekki@phys.unsw.edu.au

Table 1. Model parameters for DMSH-LMC interaction.

Model name	$M_{\text{dms}} (\times M_t)^a$	$r_p (\times R_d)^b$	Orbital eccentricity (e)	Inclination angle (θ°)	Comments
M1	0.05	0.5	1.0	180	the standard model
M2	0.01	0.5	1.0	180	less massive DMSH
M3	0.02	0.5	1.0	180	
M4	0.1	0.5	1.0	180	more massive DMSH
M5	0.05	0.5	1.0	0	prograde encounter
M6	0.05	1.0	1.0	180	larger r_p
M7	1.0	3.0	0.5	180	distant encounter
M8	0.05	0.01	1.0	90	almost head-on collision
M9	0.1	0.01	1.0	90	
M10	-	-	-	-	isolated model

^a The mass of a dark matter subhalo (DMSH) in units of the mass of the LMC (M_t).

^b The pericenter distance of the DMSH in units of the LMC disk size (R_d).

parameter survey of tidal interaction between the LMC and the dark matter subhalos (DMSHs). The time scale of a LMC-DMSH merger/collision event (t_m) can be estimated as follows (e.g., Makino & Hut 1997);

$$t_m = \frac{1}{n_h \sigma v}, \quad (1)$$

where n_h , σ , and v are the mean number density of the DMSHs within the Galaxy, the geometrical cross section of the LMC, and a relative velocity between a DMSH and the LMC. We here estimate n_h for the central 50 kpc of the Galaxy (corresponding to the pericenter of the LMC orbit) and assume that $\sigma = \pi R_d^2$, where R_d is the LMC size and v is velocity dispersion ($= v_c / \sqrt{2}$, where v_c is the circular velocity thus 220 km s^{-1}) of the Galaxy halo. If we use the results of the latest cosmological simulations (e.g., Springel et al. 2008), which can resolve 300,000 subhalos of the Galaxy, we can estimate that the total number of subhalos (N_h) with masses larger than $\sim 5 \times 10^8 M_\odot$ within 50 – 100 kpc is about 20 (from the results in their Figs. 9 and 11). Then we can derive t_m as follows;

$$t_m = 2.1 \left(\frac{N_h}{20} \right)^{-1} \left(\frac{R_d}{5 \text{ kpc}} \right)^{-2} \left(\frac{v}{156 \text{ km s}^{-1}} \right)^{-1} \text{ Gyr} \quad (2)$$

This suggests that the LMC-DMSH collision is not so rare and thus worth a numerical investigation.

2 THE MODEL

We numerically investigate dynamical impact of a DMSH in the Galaxy on the evolution of the stellar disk of in the LMC by using our original GRAPE-SPH code (e.g., Bekki & Chiba 2006). Since we focus exclusively on the tidal effect of the subhalo in the present study, we investigate dynamical evolution of a *purely collisionless system* for variously different model parameters of the DMSH-LMC interaction. In order to show more clearly the dynamical impact of the DMSH-LMC interaction, we do not include any other tidal effects of the Galaxy and the SMC: non-inclusion of these effects greatly helps us to grasp essential ingredients of the tidal effect from a DMSH.

Since the details of the models for the LMC and numerical methods and techniques are given in BC05, we here briefly describe them. The LMC is modeled as a fully self-gravitating system and composed of a live dark halo and a

thin exponential disk with no bulge. The total mass of the dark halo, that of the disk, and the size of the disk are M_{dm} , M_d , and R_d , respectively. The mass ratio of the dark halo to the total mass is fixed at 0.7 throughout the paper, which is consistent with the observation by v01. We show the results of the models with the total mass ($M_t = M_{\text{dm}} + M_d$) of the LMC being $2 \times 10^{10} M_\odot$ within the tidal radius (r_t) of 15 kpc (e.g., v01, BC05) in the present study.

We use the “NFW profile” (Navarro, Frenk & White 1996) adopted in B05 for the radial density profile of the dark matter halo of the LMC and distribute the dark matter particles only within r_t . The radial (R) and vertical (Z) density profile of the initially thin disk of the LMC are assumed to be proportional to $\exp(-R/R_0)$ with scale length $R_0 = 0.2R_d$ and to $\text{sech}^2(Z/Z_0)$ with scale length $Z_0 = 0.2R_0$, respectively. In addition to the rotational velocity made by the gravitational field of disk and halo component, the initial radial and azimuthal velocity dispersion are given to the disk component according to the epicyclic theory with Toomre’s parameter (Binney & Tremaine 1987) $Q = 1.5$.

The simulations have mass and size resolutions of $2 \times 10^6 M_\odot$ and 105 pc for stars for models with particle numbers of a quarter million and $R_d = 5$ kpc. The gravitational softening length (ϵ_{dms}) of a subhalo is assumed to be different from those of dark matter and stellar particles, and models with different ϵ_{dms} are investigated. We confirm that the present results do not depend on the adopted Plummer softening lengths ranging from 140pc to 500pc.

A DMSH is modeled as a point-mass particle with a mass (M_{dms}) ranging from $0.01M_t$ to $1M_t$ and assumed to have no baryonic components such as cold gas and stars. The pericenter distances (r_p) of the DMSH-LMC interaction is a free parameter ranging from $0.01R_d$ to $3R_d$ in the present study. The initial spin of a LMC disk in a model is specified by two angles, θ and ϕ , where θ is the angle between the Z -axis and the vector of the angular momentum of a disk and ϕ is the azimuthal angle measured from X -axis to the projection of the angular momentum vector of a disk onto the $X - Y$ plane. Prograde and retrograde orbits have $\theta = 0^\circ$ and $\theta = 180^\circ$, respectively, for $\phi = 0^\circ$ in the above definition. In order to show more clearly the importance of orbital spins in the DMSH-LMC interaction, we present the results of the models with $\theta = 0^\circ$ or $\theta = 180^\circ$ and $\phi = 0^\circ$.

We consider that the lopsided distribution of older stars in the LMC (v01) is short-lived and thus can be formed

from recent tidal interaction with a DMSH within less than 1 Gyr ago. Since the observed bar contains a significant fraction of intermediate-age stars (v01; Smecker-Hane et al. 2002), we need to consider that the LMC before the tidal interaction has a well developed stellar bar. Therefore we first dynamically relax the LMC disk for ~ 7 Gyr and then we use the final barred stellar distribution (formed during the first relaxation process) as the initial one for the tidal interaction between a barred disk and a DMSH. This dynamically relaxed disk has a higher velocity dispersion and thus no spiral arms owing to long-term dynamical heating by the developed bar so that the disk can be more consistent with the observed one with no spirals for older AGB and RGB stars (v01).

Although we have investigated a large number (30) of models with different M_{dmsH} , r_p , and θ , we mainly show the results of “the standard model” in which $M_{\text{dmsH}} = 0.05M_t$, $r_p = 0.5R_d$, and $\theta = 180^\circ$. This is because this model can show more clearly a typical behavior of the off-center bar formation. In order to explain briefly dependences of the results on model parameters, we show the results of the selected ten models, for which the parameter values are shown in the Table 1. Although it is pretty obvious that the projected stellar distribution in the LMC shows an off-center bar (e.g., de Vaucouleurs & Freeman 1972; v01), previous observations did not quantify the degree of “off-centeredness” for the bar. We thus discuss the morphologies of the simulated two-dimensional (2D) distribution of older stars in a more qualitative manner in the present paper: quantitative discussion on how to define the off-centeredness of a bar needs to be done in a future paper. The surface mass-densities of old stars (μ_s) is defined as $\log_{10}\Sigma_s$, where Σ_s is the projected mass density (in units of $M_\odot \text{ pc}^{-2}$) at each of 50×50 cells for a region of $11 \text{ kpc} \times 11 \text{ kpc}$ in a model. We derive the smoothed 2D fields of μ_s by using the same smoothing method adopted in our previous paper (Bekki & Peng 2006).

3 RESULTS

Fig. 1 shows how the moderately strong dynamical impact during the collision between a DMSH and the LMC can change the overall distribution of stars in the LMC for the standard model M1. As shown in Fig. 1, the tidal perturbation of the DMSH-LMC collision can change the stellar distribution in the outer part of the LMC disk, though it can not change the shape of the central stellar bar. Owing to the retrograde tidal encounter, strong bisymmetric spiral arms can not be formed during the collision in this model. The center of the bar is coincident with the dynamical center of the LMC (i.e., the center of the mass) during and after the DMSH-LMC collision. The stellar distribution in the outer part of the disk, on the other hand, appears to be lopsided with respect to the center of the bar at $T = 0.27$ and 0.68 Gyr, which means that the simulated LMC after the collision appears to have an off-center bar. The stellar vertical structure and kinematics do not change during the collision.

Fig. 2 shows the 2D distributions of μ_s at $T = 0$ and 0.68 Gyr in the standard model. It is clearer in Fig. 2 than in Fig. 1 that the final stellar distribution of the disk at

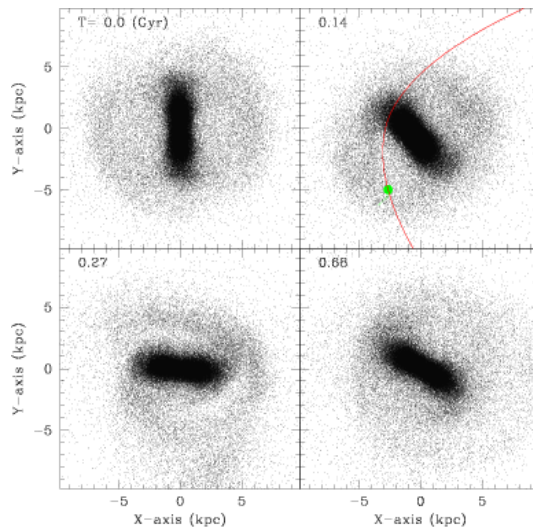


Figure 1. Time evolution of stellar distributions in the LMC projected onto the x - y plane for the standard model M1. The dynamical center of the LMC is coincident with the center of each frame and the time T in units of Gyr is shown in the upper left corner of each frame. The DMSH and its orbit are shown by a big green circle and a red solid line, respectively, in the upper right panel for $T = 0.14$ Gyr when the DMSH collides with the LMC. Note that this retrograde tidal perturbation during the collision can cause an asymmetric distribution without forming strong spiral arms.

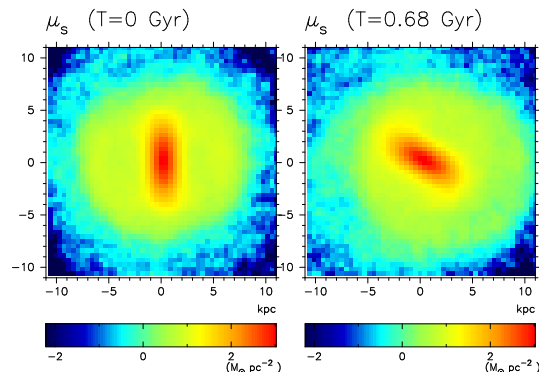


Figure 2. Initial (left) and final (right) 2D distributions of μ_s in units of $M_\odot \text{ pc}^{-2}$ (logarithmic scale) for the standard model. For convenience, the dynamical center (i.e., the center of the bar) is set to coincide with the center of each frame. It appears that the μ_s distribution after the DMSH-LMC collision is lopsided with respect to the center of the bar. This means that the bar appears to be off-center with respect to the center of the disk.

$T = 0.68$ Gyr appears to have an off-center bar: the center of the iso-density contour of $\mu_s \sim 0.5M_\odot \text{ pc}^{-2}$ is not coincident with the center of the bar. Fig. 3 confirms that the μ_s distributions along the x - and y -axes around $R = 5 - 10$ kpc are appreciably asymmetric. These results mean that the disk appears to have an off-center bar, not because the center of the bar really deviates from the center of the mass for the disk, but because the stellar distribution in the outer part of the disk is lopsided with respect to the center of the bar. These results imply that the origin of the off-center bar in the LMC is due largely to the lopsided distribution of

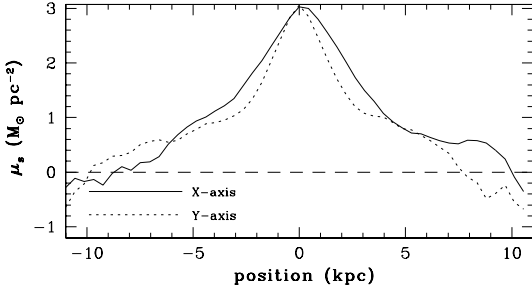


Figure 3. The radial profiles of μ_s along x -axis (solid, for particles with $|y| \leq 220$ pc) and y -axis (dotted, for particles with $|x| \leq 220$ pc) for the stellar disk at $T = 0.68$ Gyr in the standard model. For comparison, ($\mu_s = \log_{10} \Sigma_s \sim 0 M_\odot \text{ pc}^{-2}$) is shown by a dashed line. Note that the outer disk ($|x| > 5$ kpc or $|y| > 5$ kpc) shows asymmetric distributions.

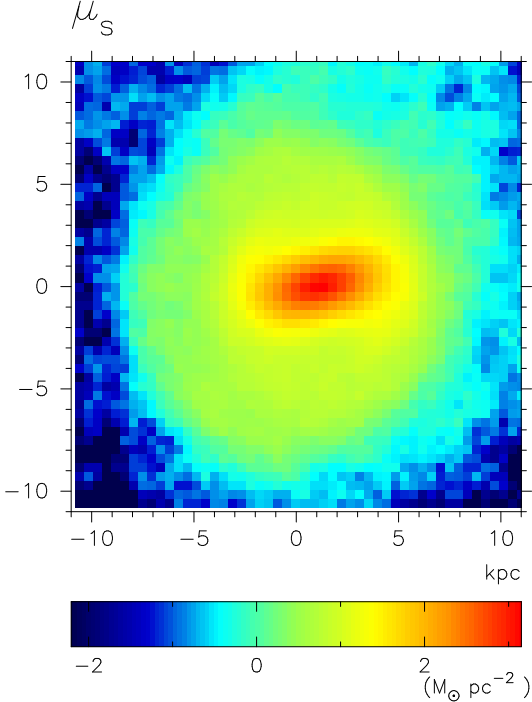


Figure 4. The 2D distribution of μ_s at $T = 0.68$ Gyr for the stellar disk that is rotated and inclined such that the distribution can be similar to the observed distribution of AGB/RGB stars in the LMC by v01. Here the center of the frame is set to be coincident with the center of the iso-density for the outer part of the simulated disk ($\mu_s = \log_{10} \Sigma_s \sim 0.5 M_\odot \text{ pc}^{-2}$): the center of the bar deviates ~ 1 kpc from the isophotal center. The disk appears to have an off-center bar in this 2D distribution.

stars in the outer part of the LMC *with respect to the center of the bar*: the dynamical center of the LMC is coincident with the center of the apparently off-center bar.

It is found that the simulated 2D distribution of μ_s at each time T depends strongly on viewing angles of the LMC disk. Fig. 4 shows the final 2D distribution of μ_s (i.e., $T = 0.68$ Gyr in M1) that is rotated by 220° in the x - y plane and then inclined by 30° with respect to the x - y plane. These rotation and inclination angles are chosen such that the distribution can be compared with the observed one for older stellar populations by v01. It is clear in Fig. 4 that the cen-

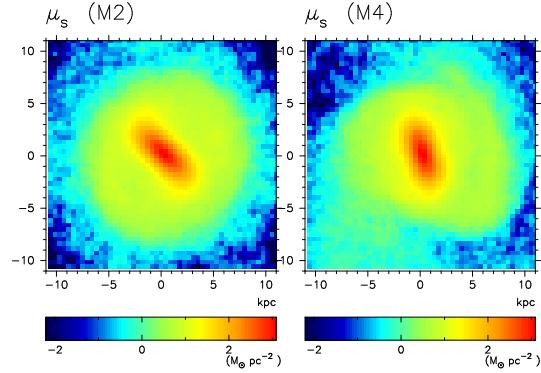


Figure 5. The same as Fig. 2 but for the models M2 (left) with $M_{\text{dmsh}} = 0.01 M_t$ and M4 (right) with $M_{\text{dmsh}} = 0.1 M_t$.

ter of the bar appears to deviate from the center of the disk (which is defined by the center of the iso-density contour for $\mu_s \sim 0.5 M_\odot \text{ pc}^{-2}$). Thus these results suggest that the origin of the off-center bar in the LMC can be closely associated with the past collision between a DMSH and the LMC.

Parameter dependences of the present study are summarized as follows. Firstly, only the models with $M_{\text{dmsh}} \geq 0.02 M_t$ can show apparently off-center bars after the DMSH-LMC collision. Fig. 5 shows that the final disk of the LMC in the model with $M_{\text{dmsh}} = 0.01 M_t$ (M2) does not have an off-center bar whereas the disk in the model with $M_{\text{dmsh}} = 0.1 M_t$ (M4) has an apparently off-center bar and a significantly asymmetric distribution in its outer part. The absence of a remarkable off-center bar in the model M2 suggests that there is a threshold M_{dmsh} for the off-center bar formation by the DMSH-LMC collision. The final μ_s distribution in the model M4 is too asymmetric to be consistent with the observed one by v01, which suggests that there can be a range of M_{dmsh} required for explaining well the observed stellar distribution with a less disturbed morphology in the LMC.

Secondly, the models with retrograde encounters (e.g., M1) can show more clearly off-center bars than those with prograde encounters (e.g., M5). Thirdly, the models with larger r_p ($\geq R_d$) do not show off-center bars (M6), which means that there is a threshold r_p below which an off-center bar can be formed from the DMSH-LMC collision. Fourthly, the models with large M_{dmsh} and large r_p (i.e., distant encounters with more massive subhalos) do not show remarkable off-center bars (M7). The model M8 in which a DMSH can make an almost head-on collision from the polar-axis of the LMC shows an off-center bar more clearly *just after* the collision without forming rings and spirals: the off-center appearance is short-lived. This result implies that if the off-center bar of the LMC can form from an almost head-on collision between a DMSH and the LMC, the collision should happen very recently (i.e., within less than 0.1 Gyr). Formation processes of the off-center bar in M8 are essentially the same as those of off-center bars/nuclei seen in colliding ring galaxies like NGC 922 (e.g., Wong et al. 2006)

4 DISCUSSION AND CONCLUSIONS

We consider that the LMC-SMC-Galaxy interaction alone can not explain the off-center bar seen in *older stellar populations* (v01) in the present study. It should be, however, stressed that previous simulations (e.g., BC05; BC07; Mastropietro et al. 2005) that failed to reproduce the off-center bar in *older stars* of the LMC have not explored past orbits of the MCs consistent with the latest proper motion measurements (e.g., K06): there could be some orbital models consistent with K06 in which the SMC can interact/collide with the LMC in a retrograde sense and therefore induce the off-center bar formation LMC without forming remarkable spirals. Accordingly, although previous simulations did not support retrograde tidal interaction between the MCs (BC07), it would be fair to say currently that tidal perturbation from the SMC can not be completely ruled out as the mechanism for the off-center bar formation.

We have first shown that the observed peculiar non-axisymmetric structure (i.e., off-center bar with no remarkable spirals) in the older stellar populations can be due to the past interaction between the LMC and a low-mass subhalo with the mass as large as $\sim 5\%$ of the total mass of the LMC (i.e., $M_{\text{dmsh}} \sim 5 - 10 \times 10^8 M_{\odot}$). Recent observational and theoretical studies on the ultra-faint dwarf galaxies have suggested that there can be a minimum halo mass of $10^9 M_{\odot}$ for the formation of galaxies (Strigari et al. 2008): dark halos with masses less than $10^9 M_{\odot}$ can have little or no visible matter. Thus the present study suggests that the low-mass subhalo possibly responsible for the formation of the off-center bar in the LMC would have no or little visible matter (such subhalos are referred to as “dark satellites” for convenience from now on).

Previous numerical simulations showed that the dynamical impact of a dark satellite on the HI disk of a galaxy interacting with the satellite (“dark impact”) can be responsible not only for the formation of a giant HI hole and filamentary structures in the HI disk but also for star formation in the disk (Bekki & Chiba 2006). It would be therefore possible that one of the observed HI holes (Staveley-Smith et al. 2003), the filamentary structures connecting to the 30 Doradus region (Nidever et al. 2008), and LMC 4 (e.g., Efremov 2004) were formed as a result of the collision between the LMC and a dark satellite. Since the dark impact on the LMC may well change the orbit, the orbital evolution of the LMC for the Magellanic stream model would need to be reconsidered in the context of the possible LMC-DMSH interaction.

Although dark satellites with masses of $10^8 - 10^9 M_{\odot}$ can not strongly disturb the disks of luminous galaxies like the Galaxy, they can significantly influence less massive galaxies like the LMC. Although barred Magellanic-type dwarfs are not rare (e.g., Freeman 1984), the origin of off-center bars in these dwarfs, remains unclear (e.g., Wilcots & Prescott 2004). The present results strongly suggest that even apparently isolated Magellanic dwarfs with off-center bars might have been formed from past interaction between the dwarfs and their dark satellites. The observed very peculiar morphology of the LMC appears to have made us realize a possibly important effect of dark satellites on evolution of less massive galaxies.

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REFERENCES

- Alves, D. R. 2004, ApJ, 601, L151
- Bekki, K., Chiba, M. 2005, MNRAS, 356, 680 (BC05)
- Bekki, K., Chiba, M. 2006, ApJL, 637, L97
- Bekki, K., Chiba, M. 2007, PASA, 24, 21 (BC07)
- Bekki, K., Peng, E. W. 2006, MNRAS, 370, 1737
- Binney, J., & Tremaine, S. 1987 in Galactic Dynamics, Princeton; Princeton Univ. Press.
- Cioni, M.-R. L., Habing, H. J., Israel, F. P. 2000, A&A, 358, L9
- Cole, A. A., Tolstoy, E., Gallagher, J. S. III., Smecker-Hane, T. A. 2005, AJ, 129, 1465
- de Vaucouleurs, G., & Freeman, K. C. 1972, VA, 14, 163 (dVF72)
- Efremov, Y. N. 2004, Order and Chaos in Stellar and Planetary Systems, Edited by G. Byrd, K. Kholshevnikov, A. Myllri, I. Nikiforov and V. Orlov, ASP Conf. Ser., Vol. 316. San Francisco: Astronomical Society of the Pacific, p.261
- Freeman, K. C. 1984, in Structure and evolution of the Magellanic Clouds ed. D. Reidel, p107
- Grocholski, A. J., Cole, A. A., Sarajedini, A., Geisler, D., Smith, V. V. 2006, AJ, 132, 1630 (G06)
- Kallivayalil, N., van der Marel, R. P., Alcock, C. 2006, ApJ, 652, 1213 (K06)
- Makino, J., Hut, P. 1997, ApJ, 481, 83
- Mastropietro, C., Moore, B., Mayer, L., Wadsley, J., & Stadel, J., 2005, MNRAS, 363, 509
- Minniti, D., Borissova, J., Rejkuba, M., Alves, D. R., Cook, K. H., & Freeman, K. C. 2003, Science, 301, 1508
- Navarro, J. F., Frenk, C. S., White, S. D. M. 1996, ApJ, 462, 563 (NFW)
- Nidever, D. L., Majewski, S. R., Burton, W. B. 2008, ApJ, 679, 432
- Olsen, K. A. G., Massey, P. 2007, ApJ, 656, 61
- Smecker-Hane, T. A., Cole, A. A., Gallagher, J. S., III., & Stetson, P. B. 2002, ApJ, 566, 239.
- Springel, V. et al. 2008, preprint (astro-ph/0809.0898)
- Staveley-Smith, L., Kim, S., Calabretta, M. R., Haynes, R. F., Kesteven, M. J. 2003, MNRAS, 339, 87
- Strigari, L. E., Bullock, J. S., Kaplinghat, M., Simon, J. D., Geha, M., Willman, B., Walker, M. G. 2008, Nature, 454, 1096
- van der Marel, R. P. 2001, AJ, 122, 1827
- Wilcots, E. M., Prescott, M. K. M. 2004, AJ, 127, 1900
- Wong, O. I., et al. 2006, MNRAS, 370, 1607